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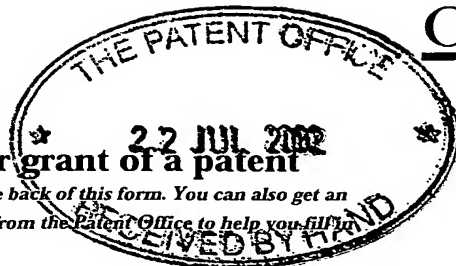
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1. Your reference P34172GB/JJH

22 JUL 2002

2. Patent application number
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0216990.2

23JUL02 E735172-1 000056
P01/7700 0.00-0216990.2

3. Full name, address and postcode of the or of each applicant (underline all surnames)

Switched Reluctance Drives Limited
East Park House
Otley Road, Harrogate, North Yorkshire
HG3 1PR

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

United Kingdom

7010712001

4. Title of the invention

Control of a Switched Reluctance Drive

5. Name of your agent (if you have one)

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

Kilburn & Strode
20 Red Lion Street
London
WC1R 4PJ

Patents ADP number (if you know it)

125001

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Country

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Number of earlier application

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11. I/We request the grant of a patent on the basis of this application.

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Date

Juliet Hibbert 22/07/02

12. Name and daytime telephone number of person to contact in the United Kingdom
Hibbert, Juliet Jane Grace
Tel: 020 7539 4200

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Control of a Switched Reluctance Drive

This invention relates to the control of reluctance machines, particularly of switched reluctance machines.

5

The control and operation of switched reluctance machines generally are described in the paper "The Characteristics, Design and Applications of Switched Reluctance Motors and Drives" by J M Stephenson and R J Blake delivered at the PCIM'93 Conference and Exhibition held in Nurnberg, Germany, 21-24 June 1993 and incorporated herein by reference. In that paper "chopping" and "single-pulse" modes of energisation of switched reluctance machines are described for operation of the machine at low and high speeds respectively.

15 A typical prior art drive is shown schematically in Figure 1. This includes a DC power supply 11 that can be either a battery or rectified and filtered AC mains. The DC voltage provided by the power supply 11 is switched across phase windings 16 of the motor 12 by a power converter 13 under the control of the electronic control unit 14. Some form of current transducer 18 is
20 normally provided to give phase current feedback. One of the many known converter topologies is shown in Figure 2, where a resistor 28 is connected in series with the lower switch 22 to provide a current feedback signal.

25 The performance of a switched reluctance machine depends, in part, on the accurate timing of phase energisation with respect to rotor position. Detection of rotor position is conventionally achieved by using a transducer 15, shown schematically in Figure 1, such as a rotating toothed disk mounted on the machine rotor, which co-operates with an optical or magnetic sensor mounted on the stator. A pulse train indicative of rotor position relative to the stator is

generated and supplied to control circuitry, allowing accurate phase energisation. Alternative methods of position detection include the so-called "sensorless" methods, in which the position is deduced from measurements of another parameter of the machine.

5

At low speeds, switched reluctance systems generally operate in a current-controlled or "chopping" mode, as illustrated generally in Figure 3 for motoring. A hysteresis current controller using "hard" chopping is often used, as shown in Figure 3(a). Typically, the voltage is applied to the phase at an angle θ_{on} in the minimum inductance region and the current rises rapidly till an upper bound I_u is reached, whereupon the switches are opened and the full reverse voltage is applied across the winding by the action of the diodes 23,24, driving down the flux and hence the current. When a lower bound I_l is reached, the switches are then closed and the current rises again. The cycle is repeated until the switch-off angle θ_{off} is reached, typically at the point of maximum inductance when the rotor poles are fully aligned with the stator poles.

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An alternative regime, known as "soft" chopping, is illustrated in Figure 3(b) in which only one switch is opened when the current reaches its upper bound, the current then decaying much more slowly through the winding, the second switch and one diode. The resulting reduction in switching frequency is often beneficial in reducing switching loss in the switches and reducing acoustic noise. Other types of current controllers are well known in the art, for example off-time controllers, constant frequency controllers, etc., and will not be described here. Their common characteristic, however, is that they all limit the current to a safe level to prevent damage to the switches and/or the machine.

20
25

At higher speeds, switched reluctance systems typically operate in the "single-pulse" mode of energisation. This mode is illustrated in Figure 4 in

which the current and linearised inductance waveforms are shown over a phase inductance period. The current rises when the voltage is applied to the phase winding at the switch-on angle θ_{on} , reaches a peak and then rolls over as the rotor poles begin to overlap the stator poles and the inductance rises. The current is limited naturally by the back emf of the circuit. The voltage is reversed at θ_{off} and the current falls at a faster rate as energy is returned to the supply and ceases when it reaches zero. There is then a period of zero current before the cycle begins again.

An alternative switching strategy uses freewheeling for a period θ_f before θ_{off} , whereby the switching circuit allows the current to re-circulate in the phase winding without an applied voltage. Figure 5 illustrates this technique and the period of zero applied voltage during freewheeling is clearly shown. Again, the current falls to zero for a time before the cycle repeats.

Thus systems generally use a chopping mode at low speeds and a single-pulse mode at higher speeds. The parameters I_u and I_l (used in the chopping mode) are normally set to values above the expected peak current of the single pulse mode, so that these parameters do not interfere with single-pulse operation. It is known to set the parameter I_u to a value which would act as a "safety net" so that if a fault condition developed in the drive the excess current would exceed I_u and cause the drive to switch off.

A special mode of operation of switched reluctance machines is the continuous current mode, as disclosed in US Patent No. 5469039 (Stephenson) and incorporated herein by reference. In this mode, the winding is re-connected to the supply before the flux, and hence the current, have returned to zero at the end of the energy return period. The phase windings therefore operate with current continuously flowing through them and are always linked by flux.

Although considered to be so unstable as to be unusable, US 5469039 discloses a method of operating in a stable manner in this region so that steady state operation is possible. Figure 6 shows a steady-state current waveform in motoring, where the current variation is quasi-sinusoidal above a "standing" value I_s . This is an important mode for systems which have to produce high levels of overload output at some points of their operating cycle. Although the efficiency of the drive falls in this mode, it allows specifications to be achieved which would otherwise require a larger machine.

While motoring operation has been illustrated in the above discussions, it is well-known that the machines operate equally well in the generating mode, in which the current waveforms are generally mirror images of the motoring waveforms.

The parameters of θ_{on} , θ_{off} , I_u , I_l , θ_f , etc., are generally functions of speed and are either computed in real time or, more commonly, stored in some form of table from which they can be read at appropriate times. The parameter values are carefully chosen in order to achieve smooth output from the machine as the speed changes. If the stored values are relatively sparse, some form of interpolation is used to give suitable parameter values at intermediate speeds. There is a particular difficulty in choosing values at the transition points between chopping and single-pulse modes, and between single-pulse and continuous current modes, where a smooth transition is desired regardless of the torque level demanded.

One solution to this problem at the transition of the chopping and single-pulse modes is to use the current control parameters as the main variable. Whereas the current level is generally held constant with speed for a given torque demand throughout the chopping range, as the speed rises to the single-pulse

mode it is known to raise the upper bound I_u gradually (and sometimes the lower bound I_l by corresponding amounts) so that the waveform gradually changes from that of, say Figure 3(a) to that of Figure 4. Once the machine has reached a speed where the current never reaches the upper current bound, the current control parameters are generally set to a high value so that they do not come into play for the rest of the speed range.

No such solution is available for the transition from single-pulse to continuous current, and careful selection of parameters is generally relied on to give a smooth transition. It is a feature of the continuous current mode that the sensitivity to angle parameters (particularly to the total conduction angle θ_c , which is the angular difference between θ_{on} and θ_{off}) is much higher than in single-pulse mode, so small differences in parameter value can produce undesirably large variations in output.

Most variable speed drive systems have to operate over a range of supply voltages and in some cases, (typically those drives operating in remote areas or from an isolated power source), that range is a very significant fraction of the nominal supply voltage. While this is generally not a serious difficulty for switched reluctance systems in the chopping mode (since the current controller is generally capable of coping with the changing current gradients), it becomes a problem in single-pulse and continuous current modes, where the torque is strongly dependent on the supply voltage. Known attempts to solve this problem include the storing of a complete set of control parameters for a range of supply voltages (i.e. introducing a further parameter, supply voltage, into the set), but this often creates unacceptable demands on storage space in the controller.

In single-pulse mode, methods of voltage compensation have been developed which cope with this variation of supply voltage. For example, US Patent No. 5724477 (Webster), incorporated herein by reference, discloses a method of modifying the speed signal so as to arrive at a set of control parameters which efficiently produce the demanded torque. Other methods of voltage compensation are known for use in the single-pulse mode.

In the continuous current mode, however, these methods are seldom satisfactory. If, for example, the machine is operating just above the transition from single-pulse to continuous current and the supply voltage then rises, use of a voltage compensation scheme such as that disclosed in US Patent No. 5724477 is likely to generate control parameters which immediately drop the machine out of continuous current. The developed torque then immediately falls, leading to a drop in speed. If the drive is in speed control, the torque error rapidly rises to compensate, which then generates new control parameters which force the system back into continuous current mode. This sequence produces significant disturbance in the torque output, which can lead to the build up of oscillations and/or other instability.

In the single-pulse mode, the developed torque is largely independent of the winding resistance (except perhaps in the smallest of machines). As the machine experiences changes in load, the winding temperature, and hence winding resistance, changes but the output of the machine is effectively independent, thus allowing the use of control parameters which are unaffected by winding resistance. In continuous current, however, the current is a strong function of the system resistance so, for given control parameters, the output fluctuates with the thermal state of the winding. Even if reliable thermal feedback from the winding were available at a reasonable cost, providing

control parameters which compensated for temperature would place an unacceptable burden on storage in the controller.

5 It is therefore clear that there is a need for a method of voltage compensation for use in the continuous current mode which is able to compensate for varying supply voltage and changes in winding temperature and also give a smooth transition from and to the single-pulse mode.

10 In accordance with a first aspect of the invention there is provided a method of controlling a switched reluctance machine in continuous current mode of operation, the switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the method comprising:

15 generating a first signal when the rotor reaches a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and

20 generating a second signal when the phase current in the phase winding reaches a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the standing current in the phase winding.

Thus the phase winding freewheels for at least part of the remainder of the conduction angle of the phase winding

25 The method may also comprise generating a third signal, which third signal causes reversal of the voltage on the phase winding. This third signal may be generated when the rotor reaches a second pre-determined position or when the phase current in the phase winding reaches a second pre-determined level higher than the first. Alternatively, the third signal may be generated when the

first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

- 5 Preferably the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding and/or the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.
- 10 According to a further aspect of the invention there is provided a control device for use in controlling the operation of a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control device comprising:
- 15 an input for receiving an angular position signal from position sensing means, said angular position signal being indicative of the angular position of the rotor with respect to the stator,
 - an input for receiving a phase current signal indicative of the current in a phase winding,
 - an output to output a control signal to a switching arrangement, and
 - 20 a processor arranged to monitor the signals received at the inputs and to generate the control signal,
 - wherein the processor is arranged to
 - generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal causes a
 - 25 voltage to be applied to the phase winding, and
 - generate a second control signal when the phase current signal indicates that current in the phase winding is at a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the standing current in the phase winding.

Preferably the processor is further arranged to generate a third signal, which third signal causes reversal of the voltage on the phase winding. The third signal may be generated when the rotor reaches a second pre-determined position or when the phase current in the phase winding reaches a second pre-determined level higher than the first. Alternatively the processor may be further arranged to generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

Preferably the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding and/or the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.

According to a third aspect of the invention there is provided a control system for use with a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control system comprising:

- a switching arrangement,
- position sensing means for generating an angular position signal indicative of the angular position of the rotor with respect to the stator,
- a current sensor for generating a phase current signal indicative of the phase current in a phase winding, and
- a control device, operatively coupled to the switching arrangement, the position sensing means and the current sensor, and arranged to receive the

angular position signal and the phase current signal and to output a control signal to the switching arrangement,

wherein the control means is arranged, in a continuous current mode of operation, to generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal
5 causes a voltage to be applied to the phase winding, and

to generate a second control signal to actuate the switching arrangement when the phase current reaches a predetermined threshold and so cause the phase winding to freewheel, thereby controlling the standing current in the
10 phase winding.

The invention can be put into practice in a number of ways, some of which will now be described by way of example and with reference to the accompanying drawings in which:

15 Figure 1 shows a typical prior art switched reluctance drive;
Figure 2 shows a known topology of one phase of the converter of Figure 1;
Figure 3(a) and Figure 3(b) show typical chopping control waveforms;
Figure 4 shows a typical current waveform in single-pulse control;
Figure 5 shows a typical current waveform in single-pulse control using
20 freewheeling;
Figure 6 shows a typical current waveform in continuous current mode;
Figure 7 shows a current waveform of the machine operating according to one aspect of the invention; and
Figure 8 shows a current waveform of the machine operating according to
25 another aspect of the invention.

The phase inductance cycle of a switched reluctance machine is the period of the variation of inductance for the, or each, phase; for example the period between maxima when the rotor poles and the relevant respective stator poles

are fully aligned. The illustrative embodiment to be described uses a 3-phase switched reluctance drive in the motoring mode, but any number of phases could be used, with the machine in either motoring or generating mode.

5 The method of control uses a combination of switch-on angle, switch-off angle and current level to trigger a period of freewheeling which controls the standing current, I_s , in the phase. Unlike previous methods of control in the continuous current mode, this method allows smooth control of the standing value of current with no abrupt dropping out of continuous current.

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Figure 7 shows a typical set of control parameters chosen according to the invention. In operation, the phase is switched on at θ_{on} in the usual way. A current level I_x is chosen, the value of which is a little below the natural peak current of the phase. The control system is arranged so that, when the phase
 15 current reaches I_x , the phase is put into freewheel until the switch-off angle θ_{off} is reached (i.e. for the remainder of the conduction angle of the phase), at which point the control becomes conventional, with both switches off. Contrary to expectation, this does not make a significant change to either the peak current or the shape of the waveform. Instead, it allows control of the
 20 level of standing current: varying I_x by a small amount gives a corresponding variation in I_s .

This unexpected result has significant benefits in control. If the supply voltage now increases or the resistance of the winding decreases due to a fall in
 25 temperature, the phase current rises faster and reaches I_x more quickly, effectively giving a shorter on time and a longer freewheel time, thus preventing an increase in the standing current I_s and stabilising the system. Conversely, a decrease in supply voltage or an increase in resistance gives a slower rise in current, increasing the on time and decreasing the freewheel time

and preventing the standing current falling. It is the combination of angle and current parameters which enable this to be achieved.

There are further benefits with this method of control in that it reduces the requirement for fine resolution of the on- and off-angles. It has previously been held that very fine resolution of these parameters is required for successful control in the continuous current mode, since the sensitivity of output to angle is high in this mode. However, this can be costly to achieve since, for example, the cost of a position resolver is very dependent on its resolution. Indeed, in some systems, the amount of continuous current which can be employed is severely limited by the degree of control available on the angle parameters. This invention, however, allows the use of a current parameter, which is easily controlled with fine resolution, to effectively "fill in" load points between steps in the angle parameters.

A variation of the method is to have two current parameters, as shown in Figure 8. The second parameter, I_y , is set above I_x and the expected peak current of the waveform. In operation, if the current rises significantly in freewheeling (i.e. after I_x has been reached) because, say, generation is taking place, then I_y can be used to switch off the second switch, effectively advancing the θ_{off} parameter. Thus the phase does not freewheel for all of the remainder of the conduction angle of the phase. The phase freewheels for a fraction of the remainder of the conduction angle of the phase.

When implementing the invention, it is generally advantageous to characterise the machine at nominal voltage and average temperature rise. This allows I_x to be chosen to accommodate both rise and fall of voltage and temperature. It is also advantageous to characterise the points before the entry to continuous current with I_x set a little bit above the natural peak current, so that when the

voltage rises and the machine would otherwise abruptly enter continuous current, the presence of the current control I_x will soften the entry and stabilise the system.

5 The skilled person will appreciate that variations of the disclosed arrangements are possible without departing from the invention, particularly in the details of the implementation of the algorithm in the microprocessor. Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. It will be clear to the skilled person that minor
10 modifications can be made to the drive circuit without significant changes to the operation described above. The present invention is intended to be limited only by the scope of the following claims.

Claims

1. A method of controlling a switched reluctance machine in continuous current mode of operation, the switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the method comprising
 - generating a first signal when the rotor reaches a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and
 - generating a second signal when the phase current in the phase winding reaches a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the standing current in the phase winding.
2. A method according to claim 1 further comprising
 - generating a third signal, which third signal causes reversal of the voltage on the phase winding, when the rotor reaches a second pre-determined position.
3. A method according to claim 1 further comprising
 - generating a third signal, which third signal causes reversal of the voltage on the phase winding, when the phase current in the phase winding reaches a second pre-determined level higher than the first.
4. A method according to claim 1 further comprising
 - generating a third signal, which third signal causes reversal of the voltage on the phase winding, when the first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

5. A method according to any preceding claim wherein the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding.
- 5 6. A method according to claim 3, 4 or 5 wherein the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.
- 10 7. A control device for use in controlling the operation of a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control device comprising:
- an input for receiving an angular position signal from position sensing
 - 15 means, said angular position signal being indicative of the angular position of the rotor with respect to the stator,
 - an input for receiving a phase current signal indicative of the current in a phase winding,
 - an output to output a control signal to a switching arrangement, and
 - 20 a processor arranged to monitor the signals received at the inputs and to generate the control signal,
 - wherein the processor is arranged to
 - generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal causes a
 - 25 voltage to be applied to the phase winding, and
 - generate a second control signal when the phase current signal indicates that current in the phase winding is at a first pre-determined level, which second signal causes the phase winding to freewheel, thereby controlling the standing current in the phase winding.

8. A control device according to claim 7 wherein the processor is further arranged to

5 generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the rotor reaches a second pre-determined position.

9. A control device according to claim 7 wherein the processor is further arranged to

10 generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the phase current in the phase winding reaches a second pre-determined level higher than the first.

10. A control device according to claim 7 wherein the processor is further arranged to

15 generate a third signal, which third signal causes reversal of the voltage on the phase winding, when the first of the following two conditions is met: the rotor reaches a second pre-determined position or the phase current in the phase winding reaches a second pre-determined level higher than the first.

20 11. A control device according to any of claims 7 to 10 wherein the first pre-determined level of phase current in the phase winding is set to be below the expected peak current of the phase winding.

25 12. A control device according to claim 9, 10 or 11 wherein the second pre-determined level of phase current in the phase winding is set to be above the expected peak current of the phase winding.

13. A control system for use with a switched reluctance machine comprising a rotor having a plurality of poles, a stator having a plurality of poles and at least one phase winding, the control system comprising:

a switching arrangement,

5 position sensing means for generating an angular position signal indicative of the angular position of the rotor with respect to the stator,

a current sensor for generating a phase current signal indicative of the phase current in a phase winding, and

10 a control device, operatively coupled to the switching arrangement, the position sensing means and the current sensor, and arranged to receive the angular position signal and the phase current signal and to output a control signal to the switching arrangement,

15 wherein the control means is arranged, in a continuous current mode of operation, to generate a first control signal when the angular position signal indicates that the rotor is at a first pre-determined position, which first signal causes a voltage to be applied to the phase winding, and

20 to generate a second control signal to actuate the switching arrangement when the phase current reaches a predetermined threshold and so cause the phase winding to freewheel, thereby controlling the standing current in the phase winding.

ABSTRACT

5 A switched reluctance drive is controlled in a stable manner in the continuous current mode in the presence of supply voltage variation. The use of a current control parameter I_x in addition to the conventional on- and off-angles θ_{on} , θ_{off} gives the ability to operate smoothly in the continuous current mode and to transition smoothly between operating modes. Once the phase current reaches a pre-determined level I_x , the phase winding is placed in a freewheel state, thereby controlling the standing current in the phase winding.

10

Figure 7

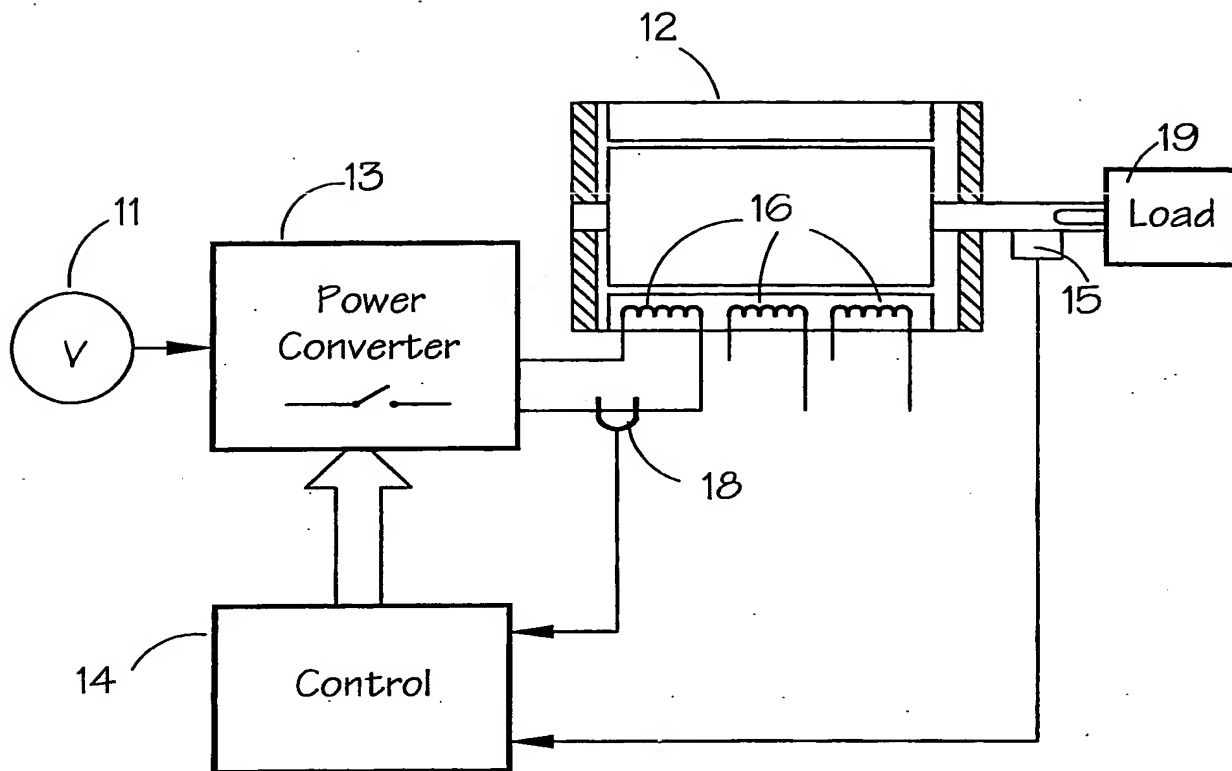


Fig 1 Prior Art

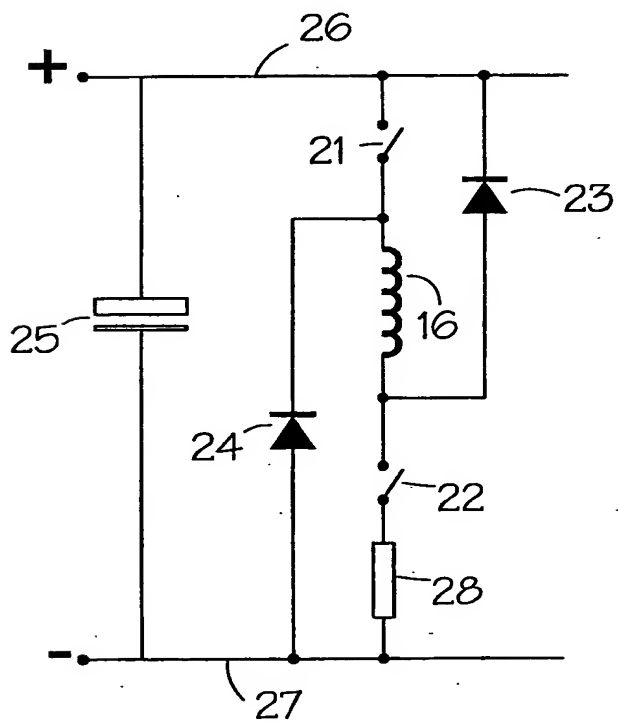


Fig 2
Prior Art

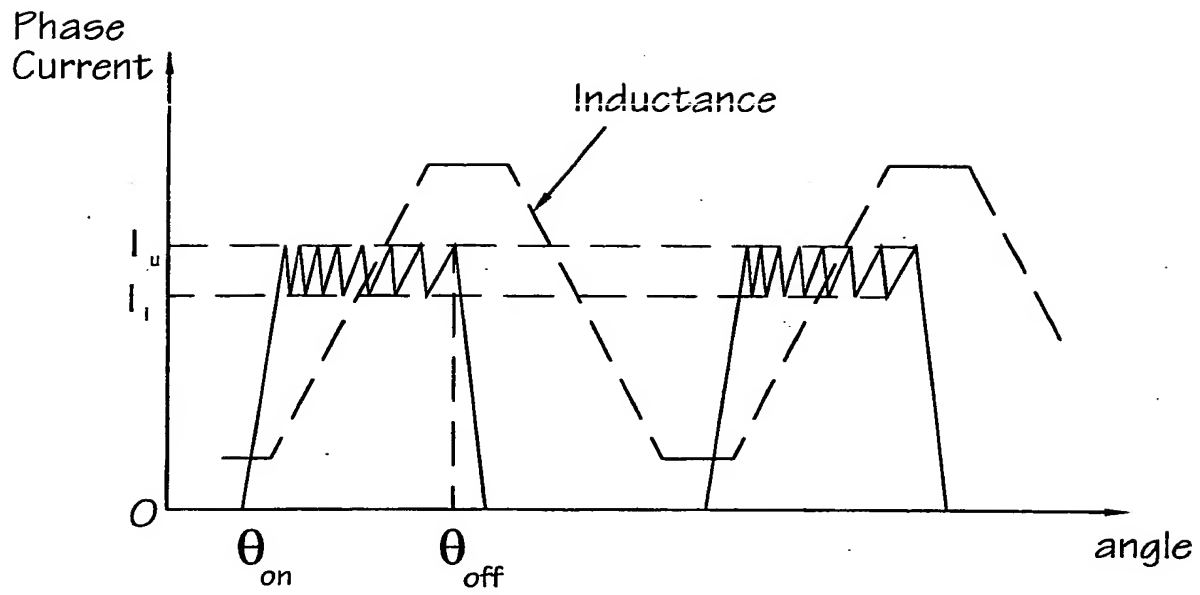


Fig 3(a)
Prior Art

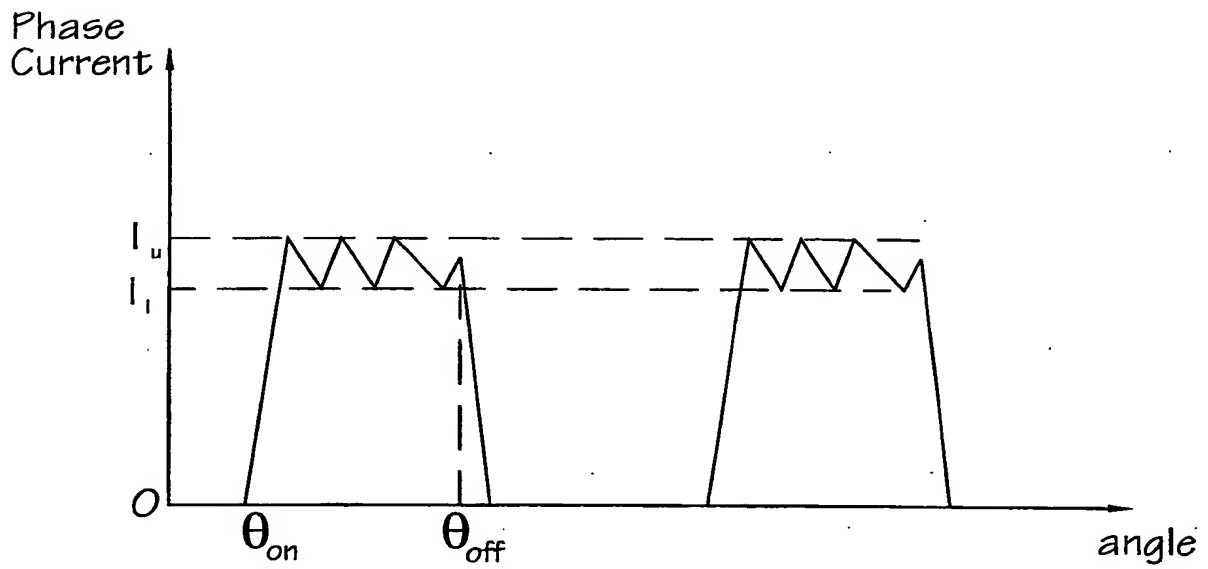


Fig 3(b)
Prior Art

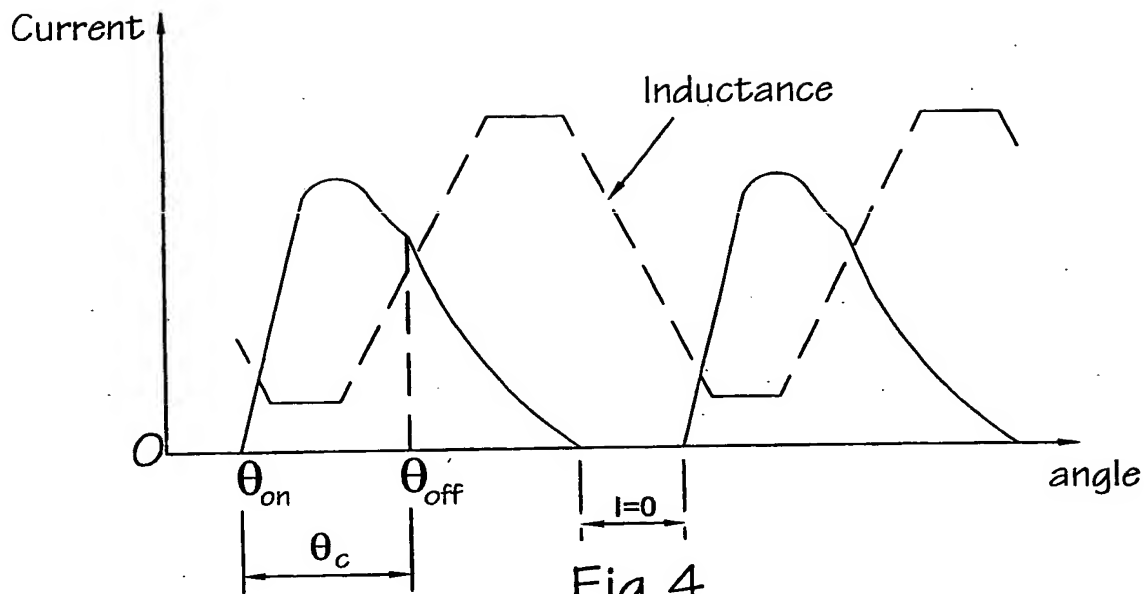


Fig 4
Prior Art

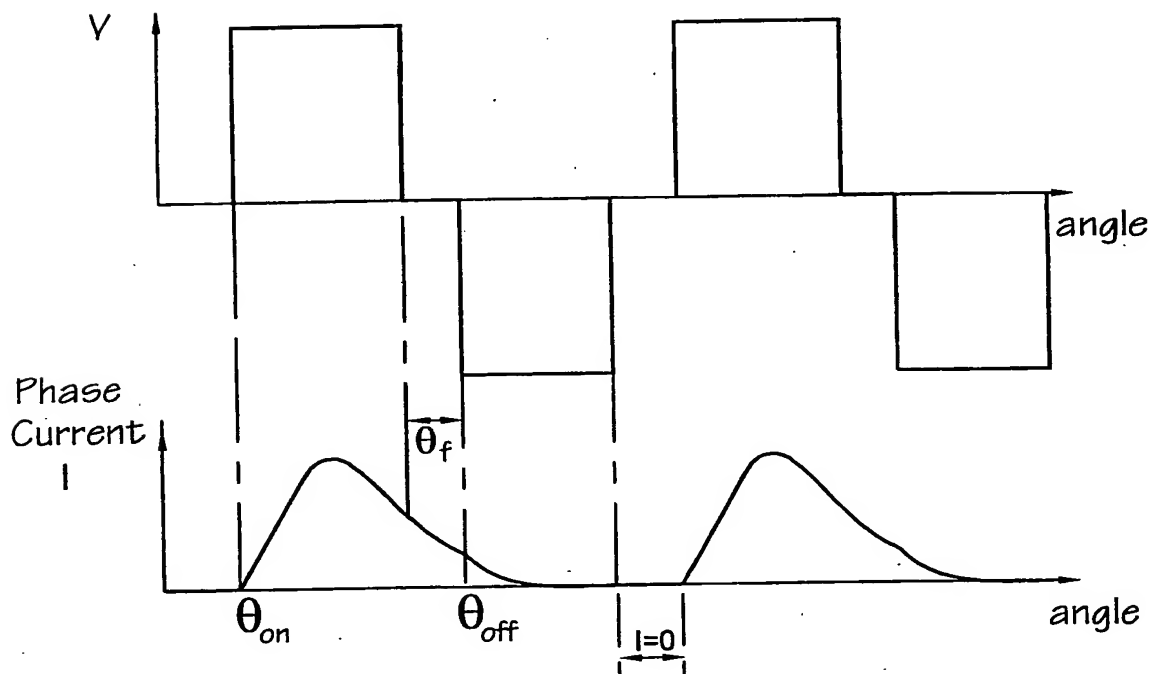


Fig 5
Prior Art

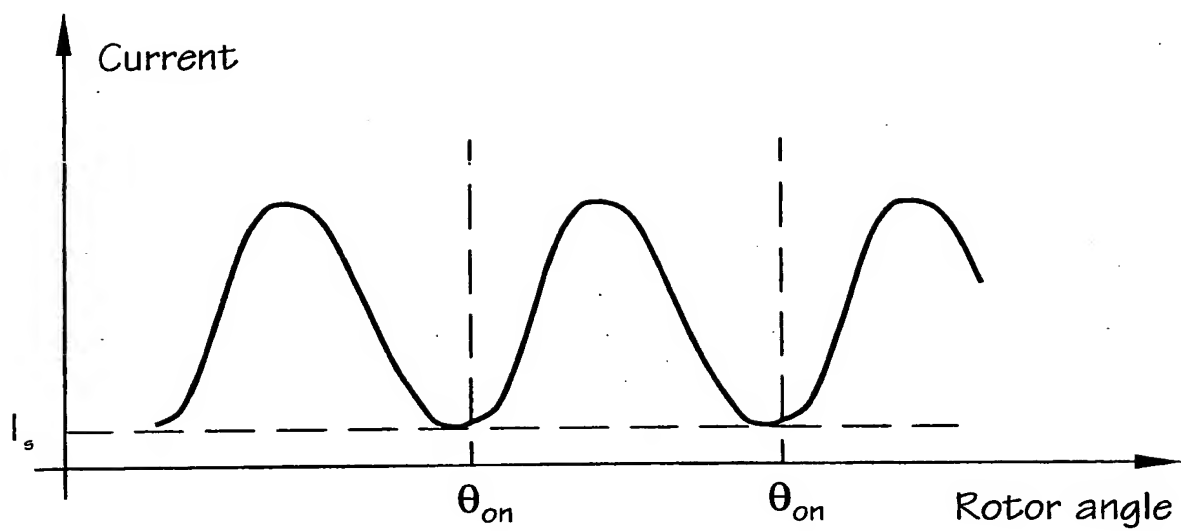


Fig 6
Prior Art

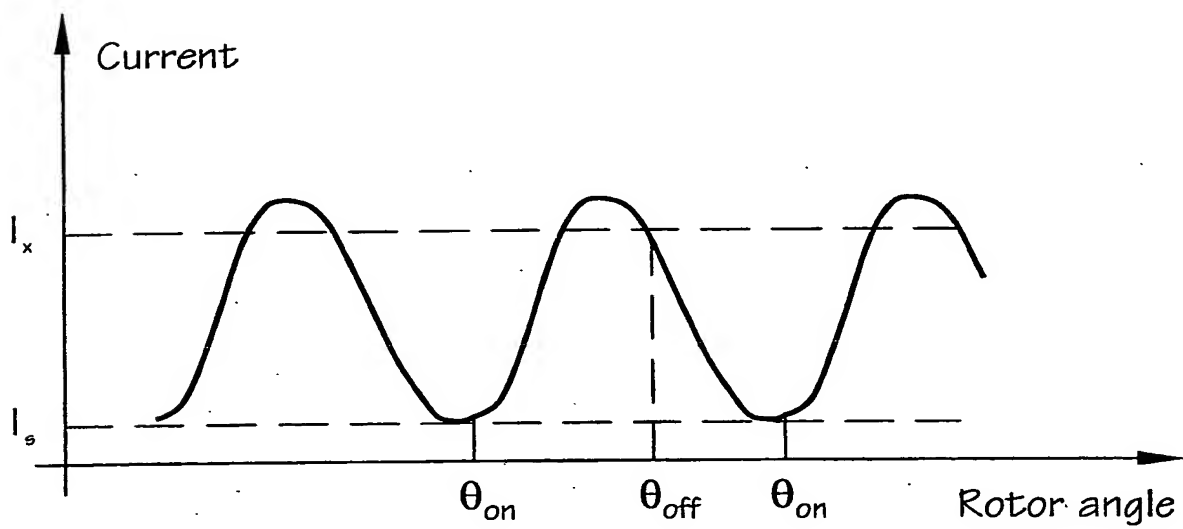


Fig 7

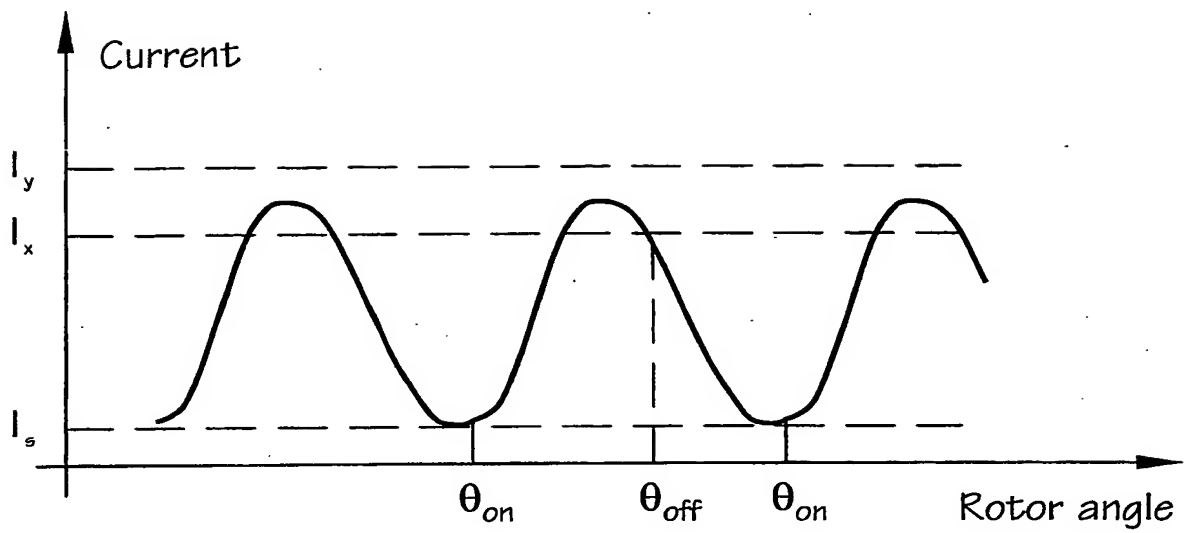


Fig 8